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FOURTH US ARMY WORKSHOP
ON
LOW HEAT REJECTION ENGINES

29–31 March 1989

Session Reports

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INDUSTRIAL UNIT OF TRIBOLOGY
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SESSION I

MATERIALS FOR INSULATED ENGINE COMPONENTS CHARACTERISTICS AND TECHNOLOGY

Rapporteur : Mr N Jackson - Ricardo Consulting Engineers plc

1. **The Application of Ceramic Materials in Reciprocating Engines**
Dr R A Wordsworth, T and N Technology Ltd

There are a number of characteristics exhibited by ceramic materials which may provide potential benefits for the reciprocating internal combustion engine. However, the brittle nature of these materials together with a variability in strength has created difficulties in applying ceramic materials to the engine environment.

Although a wide range of physical properties is available from contemporary ceramic materials, a material offering consistently high strength has yet to be developed. For sliding contact applications, desirable characteristics include good wear resistance, low friction, ability to join metals and good heat dissipation. Test results have shown that cam/follower components with cast iron cam sliding on a silicon nitride follower exhibit very low wear rates. Studies have shown that the surface finish or surface topography has a major influence on results. The application of silicon carbide to face seals has also shown substantial reductions in both friction and wear when compared with conventional materials. The rigidity of this material together with a potential for good surface finish is thought to allow hydrodynamic lubrication even under very high loadings.

The use of ceramic materials for in-cylinder components requires additional material characteristics such as high strength and low thermal conductivity. Unfortunately, no individual material offers the ideal characteristic and some compromises must be made.

Another attractive application for ceramic materials has been the exhaust port liner. The primary requirements for this application are high thermal shock resistance and low thermal conductivity. Of all the materials evaluated, aluminium titanate has been found to exhibit the most attractive characteristics.

The use of coatings for thermal insulation of combustion chamber surfaces has also been widely evaluated. Many studies are currently underway to characterise coating materials, methods of application and durability.

It is essential that good design methodology is utilised if the maximum potential is to be exploited from available material properties. This requires a thorough understanding of component loading, manufacturing technology and joining techniques in order to produce a successful component.

Discussion

Dr Wordsworth had completed his cam/follower testwork using a conventional or 'standard' oil. However, one contributor pointed out that oil quality can have a significant impact on wear test results. Dr Wordsworth admitted that additives in the oil are known to have different effects on ceramic surfaces than with conventional metallic materials. An investigation of the effect of oil quality on cam/ceramic follower combinations would therefore be desirable. Dr Wordsworth added that the cam/follower loadings used in the tests of c.1200 MPa (200,000 PSI) were outside the design limits for conventional cast iron components. It was therefore possible that the surface pitting shown in the face of the cast iron cam was caused by fatigue failure rather than wear. Further discussions centred upon the need for more information on the effect of surface finish or surface topography on friction and wear. Both asperity contact and oil retention is very much a function of surface topography. It was agreed that current definitions for surface roughness are inadequate to provide a realistic specification for friction and wear purposes. There was general support to promote surface topography as a possible idea for a future seminar or workshop.

2. **Thermally Insulated Diesel Engine**
   Dr Keith Holmes, Leyland DAF

Dr Holmes described the objectives and some results from a programme to invesigate the characteristics of a low heat rejection engine.

The overall objectives were to identify the potential for smaller cooling systems and to quantity tolerance to lower cetane fuels. The smaller cooling system was desirable to reduce both overall package size and to reduce fan power and fan noise.

The LHR engine featured a minimally cooled cylinder head with the cooling jacket restricted to a channel above the valve bridge. The cylinder head also incorporated a plasma sprayed zirconia coating on the gas face and on the valve heads. Details of the spraying technique and problems resulting from overspray were discussed.

Reductions in heat rejected to coolant had been assessed in various builds. The minimally cooled cylinder head provided a c. 20% reduction in heat to coolant and another 10% reduction was obtained through the use of coating on the remainder of the combustion chamber surface. The combined reduction of 30% in heat rejection to coolant resulted in the potential for a reduction in cooling fan power and a smaller power unit package with ultimately less vehicle drag.

The theoretical evaluation of the potential of a turbocompound system applied to the LHR engine had also been completed. This predicted substantial reductions in fuel consumption and very high power densities. These characteristics were particular desirable for military applications.

Discussion

Dr Holmes had proposed that a CVT link could be provided between the engine and turbocompound unit. There was some discussion about the practicality of this when considering the speed ranges of turbine and engine. One contributer suggested that something like an 18-20:1 ratio would be required, well beyond CVT capabilities. Dr Holmes agreed that a variable geometry power turbine would be desirable to improve the speed match with the engine.

Further discussions focused on likely temperature requirements for oils in low heat rejection engines. Dr Holmes stated that temperatures had been measured at a number of locations in the engine but these were mostly in the cylinder head. The maximum temperature of the cast iron in the valve bridge of the engine was c. 380-400^{0}C which was projected to result in a temperature of over 600^{0}C on the surface of the zirconia coating between the valves.

Thermal analysis of the piston suggested that a top ring groove temperature of 300-350^{0}C was expected. This operating temperature was beyond the capability of a conventional oil and the engine had therefore been using a 'part synthetic' oil. There was some discussion about the definition of a 'part synthetic' oil and although pressed, Dr Holmes could not provide any further information due to a confidentiality agreement. However, one contributor was able to confirm that the oil was mineral oil based and had been successfully modified to reduce a blowby problem during initial development of the LHR engine.

3. **Uncooled Opposed Piston Engine**
Professor S Timoney, University of Dublin

The power output of the two stroke engine is generally limited by thermal loading constraints. In comparison with the four stroke engine, the two stroke is attractive for low heat injection applications due to:-

a) Thermal Advantages
b) Continuous Compressive Loadings on Piston
c) No Mechanical Valves
d) Good Match with Turbo-machinery flow characteristics

An opposed piston engine, which has been the subject of a number of publications, is under investigation at the University of Dublin. One of the primary objectives of the engine design was to eliminate the piston rings. The use of ceramic coatings was not considered feasible for piston/liner contact. The engine features a monolithic ceramic liner and ringless unlubricated ceramic pistons. Early tests with both a glass ceramic and silicon carbide were not entirely successful. The latest engine build contains reaction bonded silicon nitride (RBSN). Following some initial failures, Finite Element studies have enabled re-design to reduce operating stresses. Primary design changes have been to reduce liner section thickness and to split the single liner into two with individual liners for each piston.

Engine testwork following re-design has been limited to motoring tests. No firing tests have been carried out with the new components.

Discussion

Following on from discussions concerning surface finish, one contributor was able to confirm that the surface finish on the monolithic RBSN liner was c 0.1μm Ra. This had been achieved by a diamond lapping process.

Further discussions considered the low wear rates of the liner and piston as reported by Professor Timoney. The low wear rates were interesting as the piston and liner were unlubricated. Professor Timoney pointed out that the wear rates were comparable with conventional lubricated engines. The low wear rates may be partly due to the excellent concentricity of the piston and liner under operating conditions. The design of the engine ensured very low levels of thermal distortion such that relatively uniform piston/liner contact should be achieved.

Although the latest version of the engine had shown some promising characteristics, the ringless piston concept continues to suffer problems from excessive blowby.

4. Discussion - General

A general discussion developed concerning the commercial driving force for low heat rejection engines and if there were differences in objectives between UK and US research programmes.

One contributor pointed out that the primary consideration for the majority of truck sized diesel engines is the potential to meet future emissions standards. The very high NOx levels produced by low heat rejection engines is a major problem. The current NOx reduction method of injection retard can reduce NOx to acceptable levels, but the injection retard necessary is substantial and this leads to serious degradation in both particulate emissions and fuel consumption. Other NOx reduction methods such as exhaust gas recirculation may be possible although this is not attractive for good durability. The recently announced Raprenox catalytic system may also provide a solution although this has yet to be demonstrated as a practical on-vehicle system. For these reasons, the commercial driving force for LHR engines in the short term is for non emissions sensitive areas such as military applications.

Research programmes in the US were generally applied to Diesel engines with low air motion or 'quiescent' combustion systems. UK programmes together with some European work had applied low heat rejection concepts to relatively high swirl combustion systems. Although there were some indication that this may lead to minor differences in interpretation of results, the general conclusions, particularly regarding combustion and emissions were similar.

The work of Professor Woschni, which suggested that the thermodynamic arguments for thermal insulation were seriously flawed, has now been generally rejected. However, the combustion and heat transfer characteristics of low heat rejection engines are dissililar to conventional engines and further work is required to improve understanding on a fundamental level. Many studies have now shown that thermal insulation of direct injection diesel combustion chamber can dramatically change combustion characteristics. This has often caused difficulties in providing a realistic assessment of the potential benefits of the low heat rejection engine.

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REVIEW OF SESSION II

MECHANISMS OF WEAR OF CERAMIC MATERIALS

Rapporteur : Professor T H C Childs - Leeds University

The session contained two presented papers, by Professor D Dowson on 'Mechanisms of wear of ceramic materials' and by Mr M Rainforth on 'The role of transformation in the sliding wear of transformation toughened ceramics'. These stimulated a discussion on the conditions of wear and of wear processes in engines.

Professor Dowson reminded the meeting that the oldest bearings were ceramics, from the stone age, but that subsequently metal bearings proved more convenient to manufacture and were sufficient. It has only been with the development of modern engineering ceramics that ceramic bearings have seen a renaissance. In particular the inertness of ceramics in-vivo has led to their use as parts of artificial joints in the body. Much of Professor Dowson's lecture was developed on his experience of this aspect of ceramics bearing usage, with lessons for wear simulation testing, the observation of wear mechanisms, and the growing realisation that ceramic wear mechanisms have many similarities to those of metals, albeit often at lower wear rates. A central question is whether particular operating conditions will lead to mechanically or chemically dominated wear mechanisms.

Pin-on-disc wear rigs have advantage of allowing simple specimen shapes to be tested in well-defined conditions, allowing wear rates to be quantified and compared with one another, conveniently in terms of volume lost per unit sliding distance per unit load. However the very low wear rates sometimes found with ceramics leads to great care being needed in their measurement: in the limits of low wear, surface profilometry is a useful technique for assessing volume loss. In tests over very long sliding distances, up to 2000 km, large variations, generally increases, have been found towards the end of a test. 2-fold variations in wear rates are common, variations up to 10-fold can occur: quotation of wear rates to 3 significant figures is a nonsense; and short term wear tests might be misleading for long term performance predictions.

However pin-on-disc tests have a major disadvantage in not reproducing the conformity of any particular bearing, and further they might not reproduce load, speed, temperature or environment conditions either.

Further, one should not forget that the counterface material condition could also affect the wear of the pin. Professor Dowson gave examples of 100-fold variations of the wear of polythene on different grades of alumina and of the influence of wet and dry conditions on wear rates of self-mated PSZs and various grades of alumina, in the range 10^{-4} to 10^{-9} mm^3/Nm.

Turning to wear mechanisms, he showed slides of plastic abrasion of alumina grains and talked of observations of adhesive transfer and of surface chemical reaction controlled wear mechanisms, to show all the classifications of metallic wear: abrasive, adhesive, corrosive wear apply to ceramics too; but in addition brittle fracture wear modes are important to ceramics in severe sliding conditions.

In summary, observations on a range of ceramics show their wear mechanisms to be varied as those of metals. There is a clear need for this knowledge gained from laboratory rigs operating essentially at room temperature, in dry or wet air, to be extended to the higher temperature, combustion gas and lubricant conditions of engine and proposed engine applications.

By contrast, Mr Rainforth presented a detailed research report on the wear of a range of magnesia and yttria partially stabilised zirconias sliding on steels at a variety of surface temperatures. His aim was to establish whether transformation toughening could operate on an asperity level to affect wear and generally to observe effects of temperature on wear, but the simplest fact to emerge was that different PSZs showed 10-fold differences in their wear rates, from 1.5×10^{-8} to 10^{-4} mm^3/Nm. Alloying effects, too, are every bit as complex with ceramics as with metals.

In more detail, as an example, TEM sections were shown which showed the top 0.5μm of the wear surface to be mechanically mixed with the counterface material; at 0.5μm down to 4μm plastically flowed untransformed PSZ was seen; the monoclinic transformed structure only occurred at depths below 5μm: again a complexity reminiscent of metallic wear observations.

Rainforth classified the overall wear behaviour of PSZs according to temperature. Below 300°C surface transformation was possible and when it occurred mechanical wear mechanisms operated - plastic flow and pop-out of grains - but in the absence of transformation wear occurred by chemical reactions between the PSZ and iron oxides, with removal of the reaction product. In the medium temperature range, about 500°C, trans-

rormation was not possible and wear was either mechanical - by fracture - or chemical again. In the high temperature range, above 900°C, wear was mainly mechanical - by gross plastic flow.

Apart from questions of clarification, the discussion centred on applicability of the talks to engine conditions. A group of discussions centred round effects of sliding speed, friction heating and environmental temperature on wear rate and mechanism. Effects of water vapour contamination found at room temperature in lightly loaded pin-on-disc tests might not be relevant to engine conditions, but might be replaced by other chemical reactions in combution gases, particularly with respect to the wear of piston rings and liners and of valves and valve seats.

A discussion on whether sliding or impact loadings were important to the wear of valve seats split into two camps, some feeling that the impact must be important but others pointing out that scratches (indicating sliding) were observed on worn seats and that scuffing, not failure, was the observed problem with RBSN valve/ valve seat contacts. A possiblity of valve seat problems due to impacting of deposits was also mentioned.

A concern for the integrity of ceramic coatings was expressed in the context of piston ring performance.

Returning to the theme that both surfaces of a sliding pair are important to their wear it was pointed out that ceramic on ceramic is not a preferred combination where problems of conformity occur. This led to a practical discussion of whether ceramic wear debris would cause catastrophic abrasive wear of metallic parts in mixed metallic/ceramic systems. This is clearly a danger but provided ceramic debris were micron or sub-micron sized it was felt no problem would occur - at least no worse that the problems, if any, from carbides on steels; and it was pointed out that mixed ceramic/metal cam and tappet systems already worked well.

In summary, on the one-hand ceramic wear components are successfully running in engines, and practical experience is being gained through coordinated development programmes (for example in the UK through CARE - Ceramic Applications for Reciprocating Engines). On the other hand a sound view of ceramics wear science involving both mechanics, materials science and chemistry, is building up from laboratory tests in non-engine conditions. The linking of the two is an area for future concentration.

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REVIEW OF SESSION III

SURFACE-LUBRICANT INTERACTION AND FRICTION

Rapporteur : Dr G M Hamilton, Reading University

1. Introduction

The principal speaker was Dr A R Lansdown of the Swansea Tribology Centre. He presented what he regarded as a realistic view of the problems of lubricating low heat rejection engines (LHRs). He pointed to two main difficulties. These are that the sliding surface of parts of the engines will be above 300^{o}C and, less obviously, the fact that the materials from which they are constructed will lead to enhanced flash temperatures. These high flash temperatures occur because ceramics are for the most part very rigid and have a low thermal conductivity.

Considerable research effort has produced liquids which make better high temperature lubricants than mineral oils, but they still suffer oxidative degradation above 280^{o}C when exposed to these high temperatures for periods greater than 1000 hours. Above 450^{o}C they lose their thermal stability completely.

At the temperatures proposed for the LHRs the viscosity of most available lubricants have fallen below 3 cS. They are thus incapable of supporting high specific pressures by the traditional hydrodynamic methods. It becomes necessary to rely on boundary additives. Dr Lansdown outlined the three main types of additive available but came to the conclusion that only those which depend on chemical reaction with the surface would be successful. One problem might be that, at the prevailing high temperatures, these materials would be unacceptably corrosive.

General arguments, based on the use of the Stribeck curve, suggested that it would be necessary to accept a relatively high coefficient of friction in the sliding contacts. This would mean that some of the thermodynamic advantages of the engine might have to be traded off against higher mechanical losses. When this point was raised in the subsequent discussion it was explained that improved thermodynamics was only one aspect of the design. LHRs have considerable additional advantages which stem from the fact that they do not require conventional cooling circuits and are thus much less bulky. Their specific power rating is much higher.

2. Oil Sampling

In addition to Dr Lansdown there were two other explicit presentations. Dr M F Fox of Leicester Polytechnic gave a resume of his long series of experiments in which he extracts samples of the lubricant, from a working engine, in the region of top-dead-centre. Two sites were favoured - just behind the top ring groove and just above it. It is thus necessary to attach a system of flexible pipes to the piston and bring them out through the crank case. This technique has now been perfected and the linkage runs for several hundred hours without failure.

In the top ring groove he found that the oil had suffered severe oxidation and reduction of base number. However this was comparatively mild compared with the condition of the oil above the ring groove. Based on the chemical evidence, Dr Fox was of the opinion that this part of the engine runs much hotter that expected. He was doubtful whether the traditional finite element methods of calculating these temperatures were satisfactory. In discussion the audience was not completely in agreement with this view. They felt that the oil in this position was subject to a non-equilibrim environment and that it would be very difficult to estimate its temperature simply from its subsequent chemical condition. Similar arguments had been heard the previous day about the changes in crystal structure at the running surface of the ceramics. However it was felt that the state of oil did confirm Dr Lansdown's general scenario, that traditional oils were not going to be suitable at any higher temperatures.

There was also considerable interest taken in Dr Fox's remark that he sometimes experienced difficulty in obtaining consistent sampling rates. The difficulty here was felt to be one of quality control in the selection of the engine components used in the tests. These frequently show wide differences in surface finish and out-of-roundness.

The oil industry had found it was necessary to go to considerable expense to maintain consistency in both the selection of components and the quality of the 'build' of the engine itself. Considerable experience of getting reproducible results from small engines had been obtained in the development of the standard oil evaluation tests. Dr Fox considered that his sampling technique was reliable provided it did not rise above 1 ml/hour.

3. Fuel Pumps and Simulation Tests

The other formal presentation was by Dr M Kanakia of the Belvoir Laboratory in San Antonio. Again he was concerned with the difficulties of lubricating at high temperatures but this time in the nozzle region of fuel pumps where coking was a common problem. The pump parts were also subject to unacceptable rates of wear. He showed how extensive screening of both the fuels and additives could be done with a conventional Cameron-Plint vibrating wear tester. Using a simple ball-on-plate geometry he found that, above 180°C, there was a distinct change in the character of the friction trace accompanied by a sharp fall in the contact resistance. His results covered a wide range of aviation fuels and additive packages. No firm conclusions had yet been reached.

There was considerable audience participation in this item and a number of suggestions were for interpreting the results. It was also felt that the contact conditions needed to be further simplified if a full understanding of the additive interaction with the surfaces was going to be obtained. During this discussion Dr P Cann gave an account of her recent work at Imperial College on the formation of polyphosphate films in a range of contact conditions. It was known that similar films formed in the Cameron-Plint machine and that they might help to explain some of Dr Kanakia's results. She also made the more general remark that it would be helpful to use infra-red techniques when investigating conditions inside the LHRs.

4. Surface Finish

An on-going aspect of the discussion both in this and the previous session had been the importance of specifying surface finish, both in the engines themselves, and the test equipment used in the oil tests. The point at issue being that most of the early work in this area had been on steel surfaces. These had been shown, both in the statistical work of Greenwood and Williamson and the experimental work on the onset of scuffing by Hirst and Hollander, to be capable of a simple two parameter description. The details varied from one piece of research to another but basically one specified an average surface roughness and some characteristic wavelength. There was a suggestion that the ceramics now being used tended to have almost mirror finish combined with the presence of various types of surface defect. This problem had been met before when diamond honing first became common and it was found that a cylinder bore could be made too smooth. Platform honing became the recommmended treatment. Something similar was at the root of the well known bore polishing problem. It was thus felt that further work was necessary on the specification of surface finish in relation to the lubrication of ceramics.

5. Experience with LHRs

At the end of the session Dr E Schwartz gave an account of the present state of the experiments being conducted on LHRs by the US Army. He showed a particularly impressive slide of a prototype LHR delivering 1450 HP alongside a standard 440 HP unit. Visually both engines appeared to be about the same size. He also reported experiments on a rather more advanced 250 HP unit. The engines are in 'hybrid' condition with traditional steel cylinder liners but using ceramic and titanium components on the piston. They also make extensive use of thin plasma sprayed coatings of a variety of ceramics. Temperatures of up to 285°C had been recorded near the top ring and 380°C underneath the centre of the piston crown. The programme had reached the stage where they were able to carry out 400 hour standard oil evaluation tests. Among the more successful lubricants was Krytox 1645 - a fluorinated ether. Polyphenyl ethers had also been used.

6. Conclusion

The general feeling of the meeting was that the designers were showing considerable optimism in building these engines in the face of the present state of lubrication technology. While it was possible to keep them operational for sufficient time to complete the tests; it was not obvious that it would be possible to get the long term wear rate down to an acceptable value. A modern commercial truck engine is expected to be capable of running for upwards of 25000 hours. It was felt that there might be a case for starting a long term program, seeking out a new family of liquid lubricants and additives, that would be suitable for the range 300°C - 450°C. Such materials would of course be of widespread techno-logical interest.